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ABSTRACT

The advanced Very High Temperature gas-cooled Reactor (VHTR), which is currently being developed, achieves simplification of safety through reliance on innovative features and passive systems. One of the VHTRs innovative features is the reliance on ceramic-coated fuel particles to retain the fission products under extreme accident conditions. The effect of the random fuel kernel distribution in the fuel prismatic block is addressed through the use of the Dancoff correction factor in the resonance treatment. However, if the fuel kernels are not perfect black absorbers, the Dancoff correction factor is a function of burnup and fuel kernel packing factor, which requires that the Dancoff correction factor be updated during Equilibrium Fuel Cycle (EqFC) analysis.

An advanced Kernel-by-Kernel (K-b-K) hexagonal super lattice model can be used to address and update the burnup dependent Dancoff effect during the EqFC analysis. The developed Prismatic Super Homogeneous Lattice Model (PSHLM) is verified by comparing the calculated burnup characteristics of the double-heterogeneous Prismatic Super Kernel-by-Kernel Lattice Model (PSK-b-KLM). This paper summarizes and compares the PSHLM and PSK-b-KLM burnup analysis study and results. This paper also discusses the coupling of a Monte-Carlo code with fuel depletion and buildup code, which provides the fuel burnup analysis tool used to produce the results of the VHTR EqFC burnup analysis.

KEYWORD: Monte-Carlo, ORIGEN-2, MCWO, VHTR, Equilibrium Fuel Cycle (EqFC) analysis.

1. INTRODUCTION

The advanced Very High Temperature gas-cooled Reactor (VHTR), which is currently being developed, achieves a simplification of safety through reliance on innovative features and passive systems. One of the innovative features of the VHTR is the reliance on ceramic-coated fuel particles to retain the fission products under extreme accident conditions. The effect of the random fuel kernel distribution in the fuel pebble/block is addressed through the use of the Dancoff correction factor in the resonance treatment. If the fuel kernels are not perfect black absorbers, the Dancoff

correction factor is a function of burnup and fuel kernel packing factor, which requires that the Dancoff correction factor be updated during Equilibrium Fuel Cycle (EqFC) analysis.

Although VHTR fuel is homogeneously dispersed in the fuel graphite matrix, the heterogeneity effects in between the fuel kernels and prismatic fuel blocks cannot be ignored. The double-heterogeneous lattice model recently developed at the Idaho National Laboratory (INL) contains tens of thousands of cubic fuel kernel cells, making it very difficult to deplete the fuel kernel-by-kernel (K-b-K), for fuel burnup analysis. In addition, it is not possible to preserve the cubic size, uniformity of the kernels, and packing factor in a prismatic fuel block. To address these complexities, a validated double-heterogeneous Prismatic Super Kernel-by-Kernel Lattice Model (PSK-b-KLM) has been developed and verified.

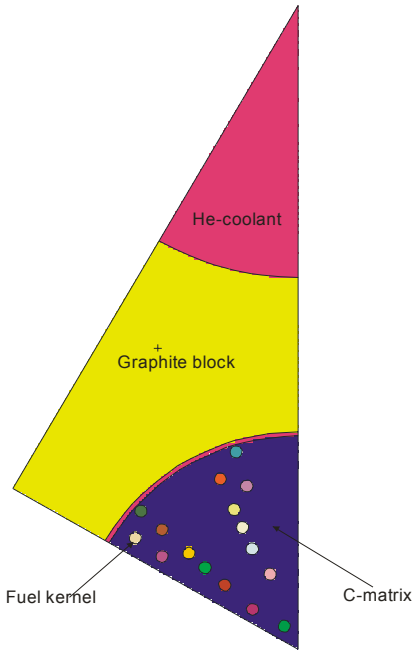
The objective of this research is to introduce the Prismatic Super Homogeneous Lattice Model (PSHLM) and PSK-b-KLM, which are used for EqFC analysis. The PSHLM results are verified by directly comparing with the burnup characteristics of the double-heterogeneous PSK-b-KLM results. Finally, Monte-Carlo was coupled with a fuel depletion and buildup code and used as a fuel burnup analysis tool to perform the fuel burnup analysis. The calculated VHTR EqFC burnup analysis results will be compared and discussed.

2. VHTR PRISMATIC SUPER LATTICE MODEL

The NGNP [1] -VHTR PSK-b-KLM developed in this study has a compact fuel zone with an outer diameter, (OD) of 1.27 cm and a helium coolant OD of 1.5875 cm, which is arranged in a unit graphite hexagonal block. The pitch (center to center) of the hexagonal fuel channel is 1.8796 cm. The graphite compact has a particle fuel kernel density of 10.5 g/cc, U-235 enrichment of 10.36% (for the initial core fuel loading), and a packing factor of 28.92%.

To build the K-b-K model from a triangular unit lattice model, first, we chose the number of fuel kernels to be 32. To preserve the packing factor, the thickness of the fuel rod layer in the model should be 0.1356 cm. Then, the fuel rod (C-matrix) is cylindrically divided into 32 equal-volume shells, such that each sub-shell contains one fuel kernel to maintain a packing factor of 28.92%, as shown in . To make the 32 kernels distribute more random-yet-orderly, the fuel kernel was allocated by the cone-shaped spiral curve around the slice median-axis in each of 32 subdivided radial shells.

Figure 1: X-Y cross-section view of a double-heterogeneous triangular fuel unit lattice model with fuel kernels.



The super lattice model consists of 12 triangular unit lattices in a hexagonal fuel block as shown in . Then, the PSK-b-KLM can be derived by replacing the 12 triangular unit lattices with the built K-b-K model from a triangular unit lattice model. To build the PSHLM as shown in from PSK-b-KLM, simply homogenize the fuel kernels in the fuel C-matrix. The developed Monte-Carlo fuel burnup analysis code will couple with the PSK-b-KLM / PSHLM to perform the fuel cycle burnup analysis.

3. EQUILIBRIUM FUEL CYCLE SHUFFLING SCHEME

The NGNP [1] (600 MWth) design with average power density of 850 W/cm^3 in the fuel blocks; can achieve an 18-month EqFC by replacing one-third of the core fuel blocks. The PSHLM and PSK-b-KLM were setup as shown in Figures 2 and 3, for the EqFC analysis.

Figure 3: X-Y cross-section view of a double-heterogeneous PSK-b-KLM with fuel kernels.

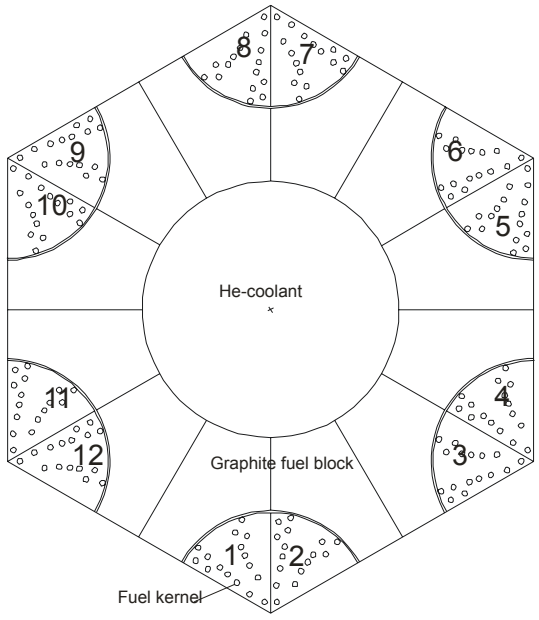
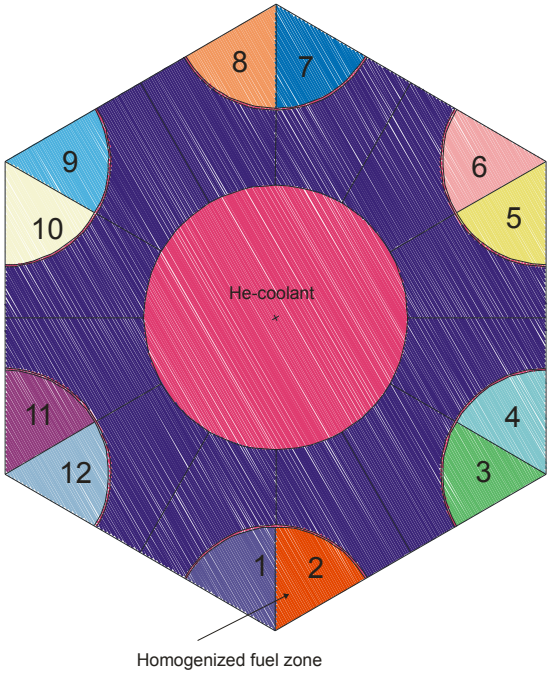


Figure 5: X-Y cross-section view of a double PSHLM with uniform homogenized fuel kernels.



The initial U-235 enrichment of the fuel block is 10.36 wt%. The one-third refueled U-235 enrichment is 14.06 wt%. The EqFC can be achieved by the following shuffling scheme. Let us assume the time steps for the 18-month fuel cycle are, 5, 12.5, 12.5, and 30 Effective Full Power Days (EFPD) for the following 17-month. At the end of initial 18-month cycle, the first third of the fuel blocks (1, 4, 7, and 10) are replaced by the new fuel blocks. Then, at the end of first refueling 18-month cycle, the second third of the fuel blocks (2, 5, 8, and 11) are replaced by new fuel blocks. At the beginning of third refueling 18-month cycle, the final third of the fuel blocks (3, 6, 9, and 12) are reset to fresh fuel kernels, which is the beginning of EqFC state. The discharged burnup of the fuel blocks 1, 4, 7, and 10 can be achieved at the end of third refueling cycle. EqFC burnup analysis of the PSHLM and PSK-b-KLM were performed and their results are discussed in the following sections.

4. EQUILIBRIUM FUEL CYCLE BURNUP ANALYSIS METHODOLOGY

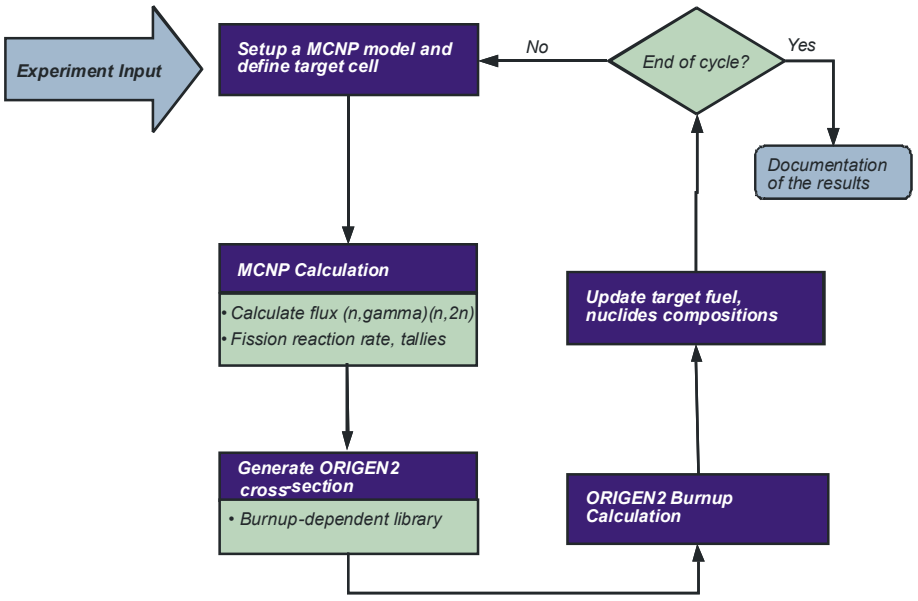
The major source of uncertainty in the fuel burnup calculation comes from burnup-dependent cross-section (XS), resonance treatment of neutron spectrum vs. fuel enrichment, and minor long-life actinide XS. The verified depletion tool, MCWO [2], (MCNP [3] coupled With ORIGEN2 [4]) was used to analyze the PSK-b-KLM and PSHLM fuel cycle burnup characteristics. MCWO, which can update the actinide XS at the beginning of each time step, is a UNIX shell script that couples the MCNP and ORIGEN2 computer codes automatically from Beginning of Life (BOL) to End of Life (EOL) without the need for any manual interface. The flow chart of the MCWO calculation is shown in Figure 4.

The validated MCWO methodology and lattice models can provide accurate neutronics characteristics of the particle fuel burnup performance. The K-b-K model takes the double-heterogeneity of the VHTR fuel unit cell into account, i.e. self-shielding of the fuel kernels, which can handle the complex spectral transitions at the boundaries between the fuel kernel and graphite matrix and treat the entire lattice at once. Particularly, the K-b-K model can analyze the mix of fissile and fertile kernels in the fuel compact burnup performance and neutronics characteristics in a K-b-K fashion.

5. RESULTS AND DISCUSSION

MCWO was used in this study to analyze the VHTR K-b-K lattice model with a double-heterogeneity for the detailed K-b-K burnup characteristic analysis. The average effective full power density of the fuel block is assumed to be 31.1 W/cm^3, which represents an effective full core power of 600 MW. The fuel burnup calculation time steps for the 18-month fuel cycle (540 EFPD) are, 5, 12.5, 12.5, and 30 EFPD for the following 17-month. The MCWO-calculated results, such as, K_∞, Xe-worth, and Pu isotopes versus EFPD are presented and discussed.

Figure 7: Schematic flow chart of MCNP coupled with ORIGEN2 (i.e. MCWO).



5.1 K_∞ Comparison of PSK-b-KLM and PSHLM versus Refueling Cycles

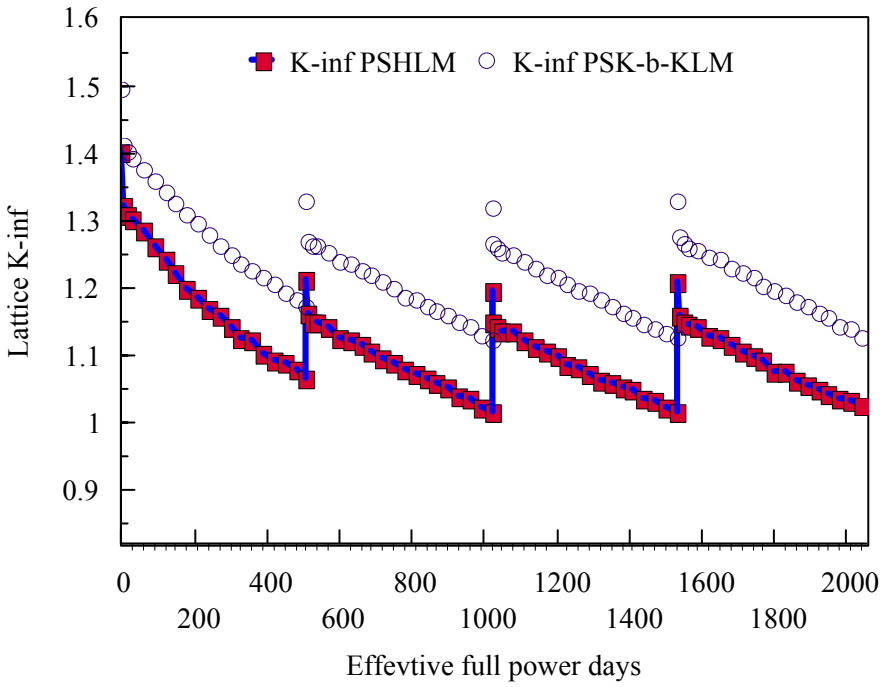
The MCNP-calculated K_∞ of the PSHLM and the double-heterogeneity PSK-b-KLM at the beginning of initial cycle (with no Xe-135 build-up) are 1.401±0.002 and 1.497±0.0015, respectively, which represents a $\Delta K = 0.096$. For the super lattice model MCNP calculations (MCNP run locally parallelized with 4 tasks, KCODE mode, 60 cycles with 2000 source neutrons), each time step required ~60 minutes computer time on a DELL-650 Workstation with dual Intel Xeon Processors (3.06 GHz), achieving a one standard deviation (1σ) less than 0.3% for the fission reaction tally.

The MCWO-calculated K_∞ of a super PSHLM versus refueling cycles (540 EFPD) during EqFC analysis is shown in Figure 5. At the beginning of each refueling cycle, four defined fuel blocks in the model are reset to fresh fuel, which causes K_∞ to jump as shown in Figure 5. Figure 5 also shows a rather constant Δk (averaged) of 0.112 from the beginning of life (BOL) to the end of life (EOL) between the PSK-b-KLM and PSHLM. The same small ΔK difference between the K-b-K and the homogenized lattice model in a VHTR hexagonal fuel block system was also observed and discussed in Reference 5.

The Fissions per Initial heavy Metal Atom (FIMA) at the initial discharged fuel burnup (540 EFPD) is 7.0%, (67.2 GWd/t). However, the discharged fuel high burnup FIMA at the end of 3rd refueling cycle (1620 EFPD) reaches 21.00% (202 GWd/t).The K_∞ of PSK-b-KLM at the end of EqFC state is 1.11, which provides adequate excess reactivity for the neutron leakage compensation and VHTR power load control. The

results shown in Figure 5 suggest that a simpler homogenized super lattice model, such as the model shown in Figure 3 with a constant bias correction, to perform the whole VHTR core EqFC analysis.

Figure 9: K_∞ comparison of PSK-b-KLM and PSHLM versus EFPD.



5.2 EqFC Xe-worth at the beginning of the Refueling Cycles

Using the formula Xe-reactivity worth $\Delta\rho_{Xe}$ (\$) = ℓn ($K_{Xe}/K_{Xe=0}$) / delayed neutron fraction (0.0072), the MCWO-calculated $\Delta\rho_{Xe}$ of the PSHLM and PSK-b-KLM at the beginning of refueling cycles is shown in Table 1.

Table 1: $\Delta\rho_{Xe}$ comparison of the PSHLM and PSK-b-KLM at the beginning of refueling cycles.

	Initial Cycle $\Delta\rho_{Xe}$ (\$)	1st Refueling Cycle $\Delta\rho_{Xe}$ (\$)	2nd Refueling Cycle $\Delta\rho_{Xe}$ (\$)	3rd Refueling Cycle $\Delta\rho_{Xe}$ (\$)
PSHLM	-8.13	-6.18	-5.54	-5.76
PSK-b-KLM	-7.92	-6.09	-5.81	-5.66

The small $\Delta\rho_{Xe}$ difference between the PSHLM and PSK-b-KLM in Table 1, indicates that the important safety parameter $\Delta\rho_{Xe}$ provided by the PSHLM is validated by the PSK-b-KLM.

5.3 Fuel Burnup Characteristics during EqFC Analysis

The MCWO-calculated isotope kernel averaged weight ratios of U-235 / U and Pu / U versus EFPD are shown in the Figure 6. The U-235 depleted from 10.36 wt% to 4.82 wt% at the end of initial cycle, and the ratio of Pu / U increases to 1.55 wt%. From the beginning of 1st refueling cycle to the end of 3rd refueling cycle (1620 EFPD), the MCWO-calculated kernel averaged ratio of U-235 / U decreases from 14.01 wt% to 0.58 wt%, and the ratio of Pu / U increases to 2.86 wt%. Because of high burnup fuel, the Pu / U wt% larger than U-235 / U wt% at the beginning of 3rd refueling cycle. For a typical VHTR core initial U loading is about 4.9 metric tons. The refueling cycle Pu production in 1/3 core of discharged 3-burnt spent fuel is about 4900/3 kg x 2.86% = 46.7 kg.

One of the criteria in the standard definition of spent fuel, as defined by the National Academy of Sciences [6] is that the isotopic compositions of the discharged fuel should be about the same as the light water reactor UO_2 spent fuel, particularly, the Pu-240 / Pu ratio should be greater than 24%. The MCWO-calculated Pu-240 / Pu ratio versus EFPD is plotted in Figure 7. Because the burnup of the 3-burnt discharged fuel reaches a rather high FIMA 21% (202 GWd/t) at the end of 3rd refueling cycle. Figure 7 shows that the ratio Pu-240 / Pu increases to a peak of 22 wt%, then, decreases to 18 wt%. However, the ratio of (Pu-240 + Pu-242) / Pu, which is also shown in , monotonically increases to 41 wt%, which can meet the spent fuel standard.

6. CONCLUSIONS

The double-heterogeneous PSK-b-KLM used in this study can handle the complex spectral transitions at the boundaries between the kernels in a straightforward fashion and treat the entire lattice at once. The MCWO-calculated results in this study indicate that there is a rather constant ΔK_∞ between the PSK-b-KLM and PSHLM versus burnup. It shows that the PSHLM can be used in the VHTR core EqFC analysis by adjusting the constant bias ΔK. The difference of $\Delta\rho_{Xe}$ difference between the PSHLM and PSK-b-KLM is very small, which indicates that the important safety parameter $\Delta\rho_{Xe}$ provided by the PSHLM can be validated by the PSK-b-KLM. However, it suggests that a further study is needed to establish an extended correlation between the PSK-b-KLM and PSHLM over the important safety parameters, such as Doppler or temperature and void coefficients.

For the PSK-b-KLM and PSHLM studies, the MCWO models demonstrate that they can provide accurate neutronics characteristics for particle fuel burnup performance. The PSK-b-KLM model can simulate the double-heterogeneity of the VHTR fuel unit lattice without the Dancoff correction factor preparation. Particularly, the K-b-K model can analyze the mix of fissile and fertile kernels in the fuel compact burnup performance and neutronics characteristics in a K-b-K fashion. The method developed in this work can be used in the VHTR safety related confirmatory analysis. The K-b-K model and MCWO can also be used to perform the neutronics analysis for particle fuel testing in the Advanced Test Reactor (ATR). The K-b-K model can also be used in a wide variety of other applications, including advanced VHTR (both fast and thermal neutron flux Gen-IV

reactors) fuel cycle performance analysis, long life minor actinide transmutation, strong absorber depletion analysis, VHTR fuel and reactor materials test assembly design.

Figure 11: MCWO-calculated kernel averaged weight ratios of U-235 / U and Pu / U versus EFPD.

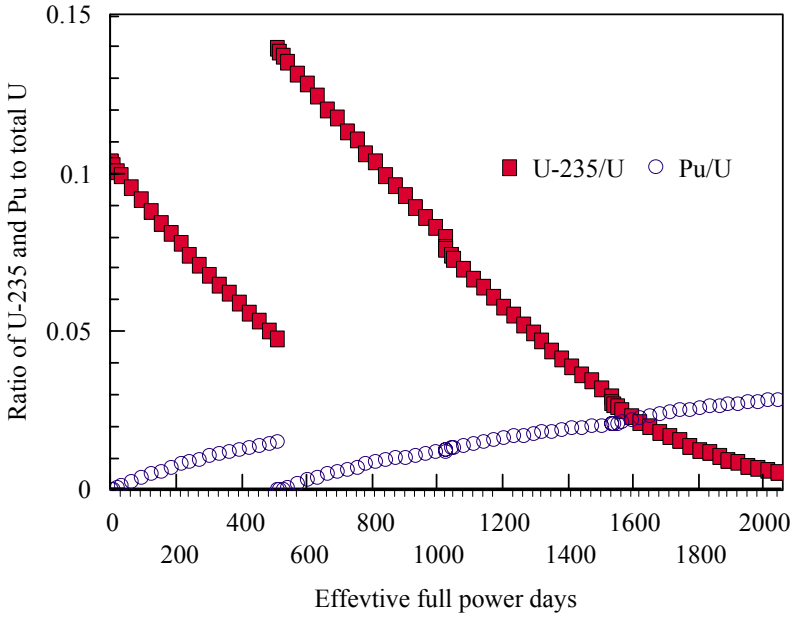
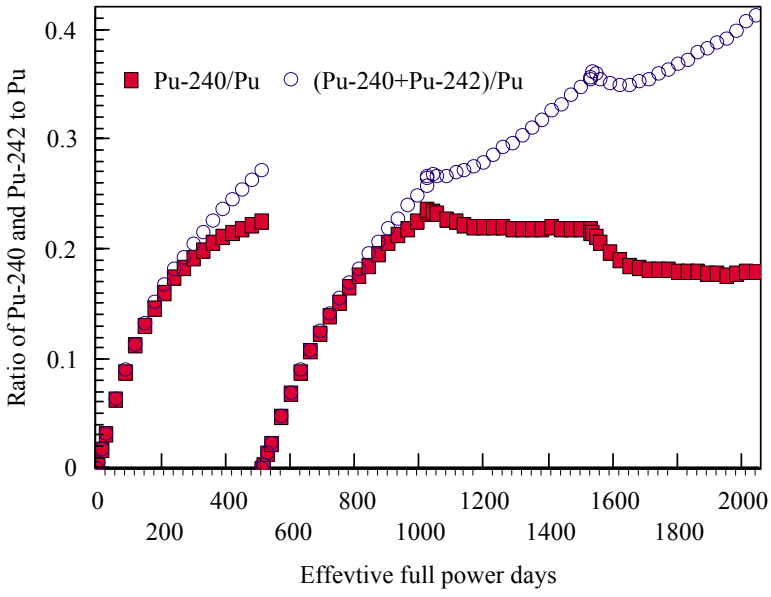


Figure 12: MCWO-calculated kernel averaged weight ratios of Pu-240 / Pu and (Pu-240 + Pu-242) / Pu versus EFPD.



References

1. NGNP Point Design – "Results of the Initial Neutronics and Thermal-Hydraulic Assessments During FY-03," Idaho National Engineering and Environmental Laboratory, INEEL/EXT-03-00870 Rev. 1, September 2003.

2. G. S. Chang and J. M. Ryskamp, "Depletion Analysis of Mixed Oxide Fuel Pins in Light Water Reactors and the Advanced Test Reactor," Nucl. Technol., 129, No. 3, pp. 326-337 (2000).

3. J. F. Briesmeister (Editor), "MCNP—A General Monte Carlo N-Particle Transport Code, Version 4C," LA-13709-M, Los Alamos National Laboratory (2000).

4. A. G. Croff, "ORIGEN-2: A Versatile Computer Code for Calculating the Nuclide Compositions and Characteristics of Nuclear Materials," Nucl. Technol., 62, pp. 335-352 (1983).

5. G. S. Chang, "VHTR Double-Heterogeneous and Homogenous Lattice Model Burnup Characteristics Comparison," Trans. Am. Nucl. Soc., Vol. 90, 37-39 (2004).

6. National Academy of Sciences Committee on International Security and Arms, Management and Disposition of Excess Weapons Plutonium, National Academy Press, 1994.